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## Magnetars: fact or fiction?

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Anomalous X-ray pulsars (AXPs) and soft gamma-ray repeaters (SGRs) are enigmatic pulsar-like objects. The energy budget is the fundamental problem in their studies. In the magnetar model, they are supposed to be powered by the extremely strong magnetic fields ( $\gtrsim 10^{14}$  G) of neutron stars. Observations for and against the magnetar model are both summarized. Considering the difficulties encountered by the magnetar model to comfortably understand more and more observations, one may doubt that AXPs and SGRs are really magnetars. If they are not magnetar candidates (including magnetar-based models), then they must be “quark star/fallback disk” systems.

### 1. Introduction

Since the discovery of pulsars in 1967, many kinds of pulsar-like objects have been discovered. Among them, anomalous X-ray pulsars (AXPs) and soft gamma-ray repeaters (SGRs) are two sorts of enigmatic sources<sup>1</sup>. Most of their persistent X-ray luminosities are in excess of their rotational energy loss rates, and they show no binary signature. Furthermore, they also show recurrent bursts. Some of the bursts (giant flares) are highly super-Eddington (with luminosity  $\sim 10^{42}$  erg s<sup>-1</sup> in the pulsating tail). Therefore, the fundamental problem in AXP and SGR studies is to find a reliable power and to balance the energy budget for both their persistent and burst emissions.

In the magnetar model for AXPs and SGRs, the compact stars are supposed to be powered by extremely strong magnetic field<sup>2,3</sup>. In addition, the strong surface dipole field ( $> B_{\text{QED}} \equiv 4.4 \times 10^{13}$  G) also provides the braking mechanism of AXPs and SGRs<sup>4</sup>. The decay of strong multipole fields ( $\sim 10^{14} - 10^{15}$  G) powers their persistent emissions<sup>3,5,6</sup>. Possible sudden release of magnetic energy (e.g., magnetic reconnection) is responsible for the bursts<sup>2</sup>. The suppression of Thomson scattering cross section in strong magnetic field may explain the super-Eddington luminosity<sup>7,2</sup>. However, there are accumulating challenges to the magnetar model in recent observations (see Section 3 below). Therefore, alternative modeling of AXPs and SGRs are not only possible but also very necessary.

AXPs and SGRs may alternatively be fallback disk systems. Accretion from a supernova fallback disk provides both the braking mechanism and the persistent emissions<sup>8,9</sup>. The period clustering of AXPs and SGRs is a natural consequence of disk braking, as shown in Fig. 1. The super-Eddington bursts could be due to the presence of a bare quark surface<sup>11,12</sup> if the compact star is a quark star<sup>a</sup>. The energy of bursts may be from elastic and gravitational energy release during star quakes<sup>16,17</sup>. Therefore, AXPs and SGRs could be “quark star/fallback disk” systems. In this scenario, only normal strength magnetic field is required  $\sim 10^{12}$  G, the same as that of normal radio pulsar.

Observations for and against the magnetar model are summarized in sections 2 and 3, respectively. Then in section 4, various alternative modelings of AXPs and SGRs are discussed. In section 5, we try to answer the question: what if no magnetars exists at all? Our conclusions are given in section 6: *AXPs and SGRs may be magnetars. However, it is also possible that they are not magnetars. If AXPs and SGRs are not magnetars (including magnetar-based models), then they must be “quark star/fallback disk” systems.*

## 2. Observations for the magnetar model

In the following we will summarize observations for the magnetar model<sup>1</sup>. The limitations of these observations are also presented.

- (1) Measurement of magnetic field through period and period derivative is often taken as confirmation of a magnetar<sup>18</sup>. This assumes that AXPs and SGRs are braked down by magnetic dipole radiation like that of rotation powered pulsars. However, if AXPs and SGRs are magnetic energy powered, then a strong particle wind will also contribute to the braking torque. The corresponding dipole field is no longer so high<sup>19</sup>. In the fallback disk model, AXPs and SGRs are braked down by propeller effect<sup>8,9</sup> and only normal strength magnetic field ( $\sim 10^{12}$  G) is required. More importantly, in the magnetar model, the dipole field mainly provides the braking torque. It is the multipole field that powers the star’s persistent and burst emissions in the magnetar model<sup>2,3</sup>. Therefore, magnetic field calculated from period and period derivatives can not be taken as confirmation of a magnetar.
- (2) The strength of multipole field may be measured from spectral lines. Possible discovery of cyclotron lines during outburst is claimed<sup>20</sup>. However, the observations are not conclusive. Furthermore, whether they are due to proton or electron cyclotron lines are not certain. In the future, if strong electron cyclotron lines are found from AXPs/SGRs (e.g., like that of 1E 1207.4-5209<sup>21,22</sup>), then AXPs and SGRs must have normal strength magnetic field. Meanwhile, the ab-

<sup>a</sup>The glitch problem for strange stars raised by Aplan<sup>13</sup> is solved in the solid quark star domain<sup>14,15</sup>. Cold quark matter is suggested in quark-clustering state there and the star behaves then like a solid star with rigidity.

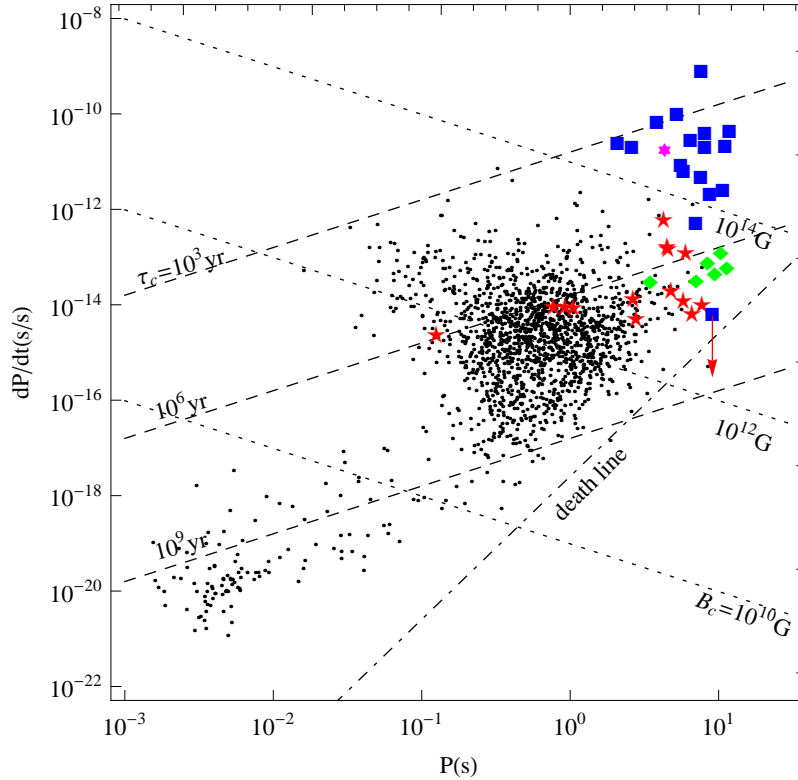


Fig. 1.  $P-\dot{P}$  diagram of pulsars. Squares are for AXPs and SGRs, the six-pointed-star is for the radio loud magnetar, the down-arrow marks the low magnetic field SGR (from McGill online catalog: <http://www.physics.mcgill.ca/~pulsar/magnetar/main.html>). Diamonds are for X-ray dim isolated neutron stars (XDINSs) (from Kaplan & van Kerkwijk 2011). Stars are for rotating radio transients (RRATs), dots are for normal and millisecond pulsars (from ATNF: <http://www.atnf.csiro.au/research/pulsar/psrcat/>).

sence of atomic features in AXP and SGR persistent emissions may imply that they are quark stars, like that of X-ray dim isolated neutron stars (XDINSs)<sup>23</sup>.

- (3) The pulsating tail seen in SGR giant flares requires a strong confinement magnetic field. In order to confine a fireball with energy  $\sim 10^{44}$  erg, a magnetic field higher than  $10^{14}$  G is required. However, this assumes that the energy is release suddenly. If the energy release is in a continuous process, the requirement on magnetic field strength is no longer available<sup>24,25</sup>.
- (4) The super-Eddington luminosity in the pulsating tail of SGR giant flares is due to magnetic suppression of Thomson scattering cross section. This point is one of the key arguments to introduce magnetar strength magnetic field<sup>7,2</sup>. However, this consideration neglects other force terms (e.g., magnetic stress). When this effect is included, only normal strength magnetic field is required<sup>26</sup>. On the other hand, AXPs and SGRs may be quark stars. The presence of a

bare quark surface will explain the super-Eddington luminosity naturally<sup>11,12</sup>. Not only the super-Eddington luminosity in the pulsating tail but also that in the initial spike are allowed if AXPs and SGRs are *bare* quark stars.

- (5) The SGR-like burst seen in the high magnetic field pulsar PSR J1846-0258 ( $B_{\text{dip}} = 4.9 \times 10^{13}$  G) is for the magnetar model<sup>27</sup>. This point is a little misleading, since there is also a low magnetic field SGR 0418+5729<sup>29</sup> with dipole magnetic field smaller than  $7.5 \times 10^{12}$  G. The corresponding explanation in the magnetar model is that it is the multipole field (not the dipole field) which is responsible for the star's bursts and persistent emissions. If we assume that AXPs and SGRs are "quark star/fallback disk" systems, their bursts are due to energy release during accretion induced star quakes (AIQs)<sup>16</sup>. If the same mechanism can occur also in PSR J1846-0258, SGR-like bursts are available. The glitch<sup>28</sup> detected in PSR J1846-0258 is consistent with the AIQ scenario.
- (6) There are also other observations which may point to a strong magnetic field, e.g., energy of persistent emissions, energy of bursts, spectral modeling, etc. However, these arguments are more model-dependent than the points listed above.

In summary, there are two assumptions in the magnetar model: a strong dipole field and a strong multipole field. Under these two assumptions, the magnetar model can explain many aspects of AXP and SGR's observations. However, up to now, we have no direct and clear evidence that AXPs and SGRs have super-strong magnetic field. Meanwhile, if we assume that AXPs and SGRs are "quark star/fallback disk" systems, these observations can be explained equally well. The period clustering and super-Eddington luminosity are natural consequences in the "quark star+fallback disk" model.

### 3. Failed predictions: challenges to the magnetar model

There are accumulating difficulties for the magnetar model in recent observations. Below, we will give several examples.

- (1) The magnetars are assumed to be born with a very short rotation period  $\sim 1$  ms. This will result in a very high magnetic field ( $\sim 10^{14} - 10^{15}$  G) through the dynamo process. Meanwhile, since there are more rotational energy and the magnetic field is very high, the corresponding supernova will be more energetic and the putative magnetar will have a very large kick velocity<sup>4</sup>. However, these two predictions are both rejected by later observations. It is found that the supernova explosion energy are of normal value by analyzing supernova remnants associated with AXPs and SGRs<sup>30</sup>. Their surrounding environment is not different from that of normal pulsars<sup>31</sup>. Therefore, from the supernova explosion point of view, we see no difference between AXPs/SGRs and normal pulsars.
- (2) Additionally, proper motion measurement of the radio emitting magnetar AXP XTE J1810-197 gives even a smaller value than that of normal pulsars<sup>32</sup>. A low

kick velocity is also required by studying the supernova remnants associated with AXPs and SGRs<sup>31</sup>. Therefore, from the kick velocity point of view, we see no difference between AXPs/SGRs and normal pulsars.

- (3) In the magnetar model, it is commonly assumed that AXPs and SGRs are braked down by magnetic dipole radiation. Therefore, they have very strong surface dipole field<sup>18</sup>. The magnetic dipole braking means that the rotation energy of AXPs and SGRs are taken away by similar processes to that of rotation powered pulsars. Therefore, we should see some rotation powered activities in AXPs and SGRs if there are really magnetars<sup>33</sup>. When applying the outer gap model to AXPs and SGRs, it was predicted that they will emit high-energy gamma-rays which are detectable by Fermi-LAT<sup>34</sup>. However, no significant detection is reported for all AXPs and SGRs in Fermi-LAT observations<sup>35,36</sup>. It is shown that there are conflicts between the prediction of the outer gap model in the case of magnetars and Fermi-LAT observations<sup>37,38</sup>. Fermi-LAT observations tell us that AXPs and SGRs must be either magnetars without strong surface dipole field or fallback disk systems. The detection of high-energy gamma-ray emissions from one high magnetic field pulsar is for the above analysis<sup>39</sup>.
- (4) The traditional picture about magnetars is that: they are young neutron stars; they have super-strong surface dipole field; their multipole field is as high as the dipole field. However, this picture is challenged by the low magnetic field SGR 0418+5729<sup>29</sup>. It has a rotation period  $P = 9.08$  s and a period derivative  $\dot{P} < 6.0 \times 10^{-15}$ . The implied surface dipole magnetic field is less than  $7.5 \times 10^{12}$  G, and a characteristic age larger than  $2.4 \times 10^7$  yr. Therefore, the traditional picture about magnetars does not apply to this source. In order to power its persistent and burst emissions, a magnetar strength of multipole field is *merely* assumed<sup>29</sup>. Whether a dynamo process can generate such a field configuration is not certain. Moreover, if people assume that such an aged magnetar (with age  $\sim 10^6 - 10^7$  yr) is still burst-active<sup>40</sup>, there will be too many SGRs in our Galaxy<sup>41</sup>. The seven XDINSs could be high magnetic field neutron stars ( $B_{\text{dip}} \sim 10^{13}$  G) with age  $\sim 10^6$  yr in the magneto-dipole braking scenario. If a magnetar at the age of SGR 0418+5729 can still be burst-active, then we should also have detected some SGR-like activities in XDINSs. However, such activities have never been observed<sup>42,43</sup>.
- (5) The radio variability of PSR J1622-4950 is assumed to be due its magnetar nature<sup>44</sup> (a “radio loud” magnetar in X-ray quiescence). Its X-ray luminosity is much smaller than other typical AXP/SGR’s X-ray luminosity. Why it has such a low X-ray luminosity? The same question also applies to the transient magnetars<sup>45</sup>. How can a magnetar strength field decay in one source and not decay in another? How can it decay some times and not decay some other times?

In conclusion, these observations provide challenges to the magnetar model. We surely require alternative ideas to understand the behaviors of AXPs and SGRs.

There may be alternative origins for strong magnetic field<sup>46</sup>. Under the general assumption of magnetic energy powered, alternative modeling of AXP and SGR's persistent and burst emissions can be done. People can even build models for AXPs and SGRs without the inclusion of any magnetar strength field.

#### 4. Alternative modelings of AXPs and SGRs

From the above analyses, we can get the conclusion that AXPs and SGRs may be magnetars. However, it is also possible that they are actually not magnetars. If AXPs and SGRs are not magnetars, then we must find alternative models to reproduce the general results observed for AXPs and SGRs. In fact, there do exist various alternative modelings of AXPs and SGRs.

- (1) It is possible that AXPs and SGRs are of wind braking. A strong multipole field provides both the persistent and burst emissions of AXPs and SGRs. A particle wind which originates from decay of strong multipole field could contribute significant braking torque<sup>19</sup>.
- (2) A fallback disk may coexist with a magnetar strength multipole field<sup>53</sup>. In this magnetar-based hybrid model, the braking and persistent emissions of AXPs and SGRs are provided by the fallback disks. While the bursts (especially giant flares) are powered by the strong multipole field, the same as the magnetar case.
- (3) Note that the super-Eddington bursts of SGRs can be explained naturally in the quark star model because of self-bound<sup>11</sup>, it is possible that AXPs and SGRs are quark stars instead of being normal neutron stars. The bursts and giant flares may be from energy release during star quakes (AIQ model<sup>16</sup>) of solid quark stars. At the same time, a fallback disk provides the braking and persistent emissions of AXPs and SGRs. This "quark star+fallback disk" scenario is discussed with details in the following section.
- (4) The color interaction between quarks in quark matter may be stronger than that in normal nucleon matter. Therefore, magnetars could be strongly magnetized quark stars instead of strongly magnetized neutron stars. A strongly magnetized quark star surrounded by a degenerate quark nova remnant may explain the observations of AXPs and SGRs<sup>47</sup>.
- (5) If the compact star is a massive white dwarf, due to a larger momentum of inertia, its rotational energy is enough to power the emissions of AXPs and SGRs. A massive white dwarf surrounded by a fossil disk may provide an alternative modeling of AXPs and SGRs<sup>48</sup>.

In the above list of discussions, models (1) and (2) are magnetar-based ones. Models (3) and (4) involve different kinds of quark stars, in either solid or liquid states. Models (1)-(4) are all in the neutron star domain (normal neutron stars or quark stars), while model (5) is based on white dwarfs. Multiwave observations of AXPs and SGRs may help us to finally distinguish between those different models

in the future.

## 5. What if no magnetars exists at all?

Now, we will outline how AXPs and SGRs can be modeled in the “quark star+fallback disk” scenario.

- (1) Spindown and persistent emissions. Neutron stars (including normal neutron stars and quark stars) are born in supernova explosions. Some of the explosive material may fallback onto the neutron star. If the fallback material carries some amount of angular momentum, they may form a disk, i.e., supernova fallback disks. Considering the period clustering and persistent emissions of AXPs and SGRs, fallback disk model for them are proposed<sup>8,9</sup>. The equilibrium period is reached when the corotation radius equals the magnetospheric radius<sup>49</sup>:

$$P_{\text{eq}} = 8 \text{ s } \mu_{30}^{6/7} M_1^{-5/7} \dot{M}_{15}^{-3/7}. \quad (1)$$

This can explain the period clustering of AXPs and SGRs naturally. In the fallback scenario, a large period derivative is not required. The low magnetic field SGR 0418+5729 is such an example. Although its period derivative is very small, its period is the same as other AXPs and SGRs. This suggests that it must also be braked down by a fallback disk<sup>50</sup>. Now its period derivative is very small since the disk lies outside the light cylinder and has little interaction with the central star.

The persistent emission spectral of AXPs and SGRs can be modeled similarly to that of accretion systems. It is shown that both the soft X-ray and hard X-ray spectrum of AXP 4U 0142+61 can be modeled uniformly employing the bulk motion Comptonization process<sup>51</sup>. The discovery of a debris disk around AXP 4U 0142+61 is for the fallback disk model<sup>52</sup>. If a massive neutron star (including normal neutron stars and quark stars) has a fallback disk it will be an AXP/SGR<sup>17</sup>. Otherwise, it will be a normal pulsar. This is why we discovery a debris disk only around an AXP not in other young normal pulsars. The optical and IR emission of this source is consistent with a gaseous accretion disk<sup>53</sup>.

- (2) Super-Eddington luminosity. Whether pulsars are normal neutron stars (mainly composed of nucleon matter) or quark stars (composed of deconfined quark matter) is a fundamental problem in pulsar astrophysics<sup>54</sup>. When the quark star model for pulsars was proposed, it was noted that the “very high luminosity event” of 1979 March 5 may imply the existence of a bare quark star surface<sup>11</sup>. Because of the bare quark star surface, both the super-Eddington radiations in the pulsating tail and in the initial spike are allowed<sup>12</sup>. The existence of a bare quark star surface may also help to explain other bursting phenomena, e.g., supernova explosions<sup>55</sup> and gamm-ray bursts<sup>56</sup>.
- (3) Energy of bursts (including giant flares). In the magnetar model, the main observational manifestations (burst and persistent emissions) are due to magnetic energy. Meanwhile, the rotational energy and the elastic energy are also present.

In the “quark star+fallback disk” model, the persistent emissions of AXPs and SGRs are due to accretion power. The bursts are due to sudden energy release of the quark star, which may include elastic energy, gravitational energy, and conversion energy from normal matter to quark matter. The collision by comet-like objects are proposed for giant flares of SGRs<sup>12,25</sup>. The corresponding times scales and pulse profiles are consistent with observations<sup>57,58</sup>. Noting the possible connection of AXP/SGR bursts and glitches, an AIQ model for AXP/SGR bursts is proposed<sup>16,59</sup>. The gravitational energy release during star quakes can be estimated as<sup>16</sup>

$$\Delta E = \frac{GM^2}{R} \left| \frac{\Delta R}{R} \right| \sim 5 \times 10^{47} \text{ erg} \frac{|\Delta R/R|}{10^{-6}}. \quad (2)$$

Therefore, during a glitch with amplitude  $\Delta\nu/\nu = 2 \times 10^{-6}$ , a maximum amount of energy  $\sim 5 \times 10^{47} \text{ erg}$  can be released. This is enough to power the SGR giant flares, including photon energy, neutrinos, and gravitational waves, etc. The glitch associated with outburst of AXP 1E 2259+586 is consistent with the AIQ model<sup>60</sup>.

Considering the trigger of star quakes, there may be two kinds of glitches in AXPs and SGRs. One kind of star quake is triggered by stress build up during the spin down of the star. The time scale for stress build up may be relatively long, and the star quake may occur deep inside the star. This kind of star quake will mainly result in transfer of angular momentum, i.e. glitches. Since the star quake happens deep inside the star, it will not accompanied by SGR-type bursts. Some of the AXP/SGR glitches and almost all of the glitches in normal pulsars (e.g., Vela pulsar<sup>61</sup>) are of this kind. We call this kind of glitches “*spin down induced glitches*”. Another kind of star quake is trigger by stress build up when the accretion matter accumulates on the star surface. The corresponding time scale for stress build up may be relatively short and the star quake mainly happens near the star surface. This kind of star quake will not only spin up the star (i.e., glitches) but also trigger SGR-type bursts. Since the magnetic field lines are anchored on the star surface, a star quake near the surface will twist the magnetic field lines, accelerate particles, thus result in SGR-type bursts (similar to the corona model of magnetars<sup>6</sup>). We call this kind of glitches “*accretion induced glitches*”. Therefore, all glitches in AXPs and SGRs are not accompanied by bursts. Instead, all bursts should associated with glitches. Because of a larger timing noise and the sparse of observations, not all glitches during outburst can be discovered<sup>1</sup>. Future theoretical and observational studies are necessary in this scenario of glitch.

Summarily, both the bursts and persistent emissions of AXPs and SGRs are understandable in the “quark star+fallback disk” model. The period clustering and super-Eddington luminosity bursts are natural consequences of this model.



## 6. Summary

We have discussed both the magnetar model and the fallback disk model for AXPs and SGRs in previous sections. There are two assumptions in the magnetar model: a strong dipole field and a strong multipole field. However, the origin of strong fields, the presence of strong dipole field and even the presence of strong multipole field are challenged by recent observations. When studying AXPs and SGRs, the magnetic dipole braking is often assumed. Many of the problems are associated with this assumption. Therefore, the study of AXP and SGR braking mechanism in the future may help us make clear some of these problems. It may also help us to distinguish between the magnetar model and the fallback disk model.

Alternative modeling in the “quark star+fallback disk” scenario is helpful to understand the nature of AXPs and SGRs. The discovery of a debris disk and a low magnetic field SGR have deepened our understanding of AXPs and SGRs. More observations in the coming decades (e.g., 10 to 30 years) will tell us clearly whether they are magnetars or “quark star/fallback disk” systems.

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